URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Task-specific Sparse MIMO Array Design for TWRI using Multi-objective CMA-ES

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Abstract

Array topology design has long been a research focus in radar imaging community, especially for multiple-input multiple-output (MIMO) through-the-wall radar imaging (TWRI), in which a small number of transmit and receive antenna elements are deployed in a certain fashion in aim of achieving the best possible focusing performance improvement. All prior works design the array topology in freespace, then apply the designed topology to through wall scenarios. In this paper, a wall parameters dependent array topology design strategy for TWRI is proposed. By incorporation of the transmission coefficients of the wall into the imaging model, two optimization criteria of minimum averaged grating lobes and minimum entropy of the image synthesizing operator are used to cast the problem as a two-objective optimization problem, which is then solved using the multi-objective covariance matrix adaptation evolution strategy (CMA-ES) algorithm. It is shown that, a less cluttered image can be achieved using this new approach for design of TWRI array topology.

1 Introduction

Multiple-input multiple-output (MIMO) radar system has been widely adopted in through-the-wall radar imaging (TWRI) since it can provide additional freedom on data observation angle and flexibility on array configuration while maintaining a rather low system complexity. In practice, a real TWRI system, however, necessitates use of only a small number of transceiving antenna elements due to practical operational concerns such as, cost, quick deployment and restriction of attainable deployment site. Therefore, deployment of a sparse MIMO array in an optimal fashion has become of importance in TWRI applications.

One method in designing a sparse MIMO array is optimization-based approach. It works by exerting a desired mask on the point spread function (PSF) and use various stochastic optimization methods to reach a globally optimum design [1,2]. However, all the aforementioned approaches only consider the free-space scenario when designing an array topology. In fact, the electromagnetic (EM) wave propagation vary drastically for different onsite TWRI operations since one would encounter different types of walls with diverse constitutive parameters (permittivity, conductivity, wall thickness, etc.). It is obvious that there exists no array topology that fit all different TWRI cases.

It is well known that for homogenous and layered walls, the EM wave's interaction with a given wall and its multiple internal reflections as the wave propagates from the antenna to the target can be modeled using transmission coefficients [3, 4]. Then, there is natural to consider incorporate the wall's transmission coefficient into MIMO array topology design. Due to the recent advances of calibration-free MIMO based wall parameters estimation techniques [5, 6], one is able to acquire the specific wall parameters, at least for a single-layer wall, before the imaging operation being carried out. Then, by exploiting this knowledge, a task-specific wall parameters dependent sparse MIMO antenna array topology design becomes spontaneously a rational approach.

This work is an attempt to take into account the wall's effects when designing array topology for TWRI purpose. In our proposed approach, we consider two optimization criteria: minimum averaged grating lobes and minimum entropy of the synthesizing operator. Then, multi-objective covariance matrix adaptation evolution strategy (CMA-ES) algorithm is employed to solve the above optimization problem [7, 8]. We note that CMA-ES, which is a so-called parameter free algorithm and rather robust to initialization, has been previously shown to outperform many other nature-inspired optimization techniques in a number of challenging antenna and EM optimization problems [7]. Various numerical examples showing the effectiveness of the proposed array topology optimization approach will be presented.

It should be noted that unlike standard compressive sensing approach [9], the goal here is not to minimize the number of antennas for a focused image but to optimally rearrange the array in a way that the elevated sidelobes introduced by the sparse array can be suppressed as much as possible for a given number of antenna elements within the confinement of a given aperture.

2 Formulation

Consider a typical 2-D MIMO TWRI geometry as below, a set of M transmitters and N receivers sparse MIMO array is employed to probe the target space using a step-frequency signal composed of P frequency bins.

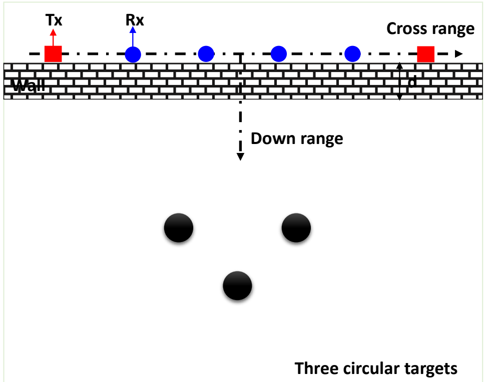

Figure 1: 2D through-the-wall radar imaging geometry.

Under the point target assumption, and using a first-order Born approximation based inverse scattering model, the image of target space can be reconstructed in a discrete form as [9],

$$I(\boldsymbol{r}) = \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{p=1}^{P} \frac{E_s\left(\boldsymbol{r}_{rm},\boldsymbol{r}_{tn},k_p\right) e^{jk_p\left(R_{tn}+R_{rm}\right)}}{T_t\left(\boldsymbol{r},\boldsymbol{r}_{tn},k_p\right) T_r\left(\boldsymbol{r},\boldsymbol{r}_{rm},k_p\right)} \tag{1}$$

Where $\boldsymbol{r}$ is the position vector of the target, $\boldsymbol{r} = (x, z)$, R_{tn} and R_{rm} are the distances from the n-th transmitter and m-th receiver to the target, T_t and T_r are the transmission coefficients from the transmitter to the target and target to the receiver, respectively, and kp is the wavenumber at p-th frequency bin.

By stacking the collected dataset from MN transceiving channels and P frequency bins together, the scattered field in (1) can be rewritten in a matrix-vector form as below,

$$y = \Theta\, s \tag{2}$$

The $(j, l)^{\text{th}}$ entry of forward operator Θ can be formulated as below [9],

$$\Theta_{j,l} = T_r(R_{rn}, r_l, k_p) T_t(r_l, R_{tm}, k_p) e^{-jk_p(|R_{rn}-r_l|+|r_l-R_{tm}|)} \tag{3}$$

For the purpose of optimizing the antenna locations using the criteria discussed later, we assume here that R_{tm} and R_{rn} are assumed to be two random variables, indicating respectively the locations of m^{th} transmitting antenna and n^{th} receiving antenna confined within a given physical aperture.

Utilizing the linear discretized operator in equation 3, the equivalence of the point spread function (PSF) of the image in (1) can be made as follows,

$$\text{PSF}(i, j) = \frac{\langle \Theta \text{e}_i, \Theta \text{e}_j \rangle}{\|\Theta \text{e}_i\|_{l2}\, \|\Theta \text{e}_j\|_{l2}} \tag{4}$$

where Θ is our synthesizing operator in equation 3, e_i is a vector taken from the natural basis having 1 at the i^{th} location and zeros elsewhere. It is obvious that the PSF for an ideal point target at i^{th} pixel is actually equal to the i^{th} column of the matrix $\Theta^H\Theta$.By shifting the position of the ideal point target, the overall PSF performance of a specific MIMO antenna array can be easily calculated using the Gram matrix $\text{G} = \Theta^H\Theta$, with whose columns normalized. In order to reduce the clutter levels in the entire radar imagery, no matter where the target is and what the shape of the target is, we propose to measure the averaged grating lobes and sidelobes level, rather than the maximal sidelobe level, for all possible PSFs corresponding to the whole target scene. We use as the first criterion for array optimization, which is defined as,

$$\overline{\text{PSF}}|_{i\neq j} = \frac{1}{N(N-1)} \sum_{\substack{i,j=1 \\ i\neq j}}^{N} |\text{PSF}(i, j)| \tag{5}$$

where $\text{PSF}(i, j)|_{i\neq j}$ stands for the off-diagonal entry of the Gram matrix. N is the size of the reconstruction scene

Apart from the intensity of the grating lobes and sidelobes level, the focusing of a target is also a rather importance measure of the performance of a specific topology. In this work, we propose to use the Shannon's information entropy of the Gram matrix as a measure to determine the degree of grating lobes and sidelobes spreading for a given array in a target irrespective manner. It is based on the assumption that if the target in a radar imagery is focused with neglectable grating lobes and sidelobes spreading, then its entropy will be low, otherwise it would be relatively high. By converting the Gram matrix into a grayscale image, the entropy of the Gram matrix is reformulated as follows,

$$En(\text{G}) = -\sum_{i=0}^{N-1} p_i \log_2 p_i \tag{6}$$

where N is the number of gray levels (256 for a 8-bit image) in the Gram matrix, p_i is the probability of an arbitrary entry having gray level i, which is often denoted by a histogram.

3 Optimization using CMA-ES

Minimal entropy in (6) means there exists only a small scale of gray levels clustered around the mainlobe in the Gram matrix, which would suppress the grating loebs and sidelobes spreading. However, the expansion of the mainlobe in this case would inevitably increase the averaged grating lobes and sidelobes level. Therefore, we conclude that the two criteria counteracts with each other and cannot be simply treated as two independent objectives. Thus, we formulate the array optimizaiton problem as a multi-objective optimization problem as follows,

$$\min F(x_t, x_r) = \left[\, \overline{\text{PSF}}|_{i \neq j} \;\; En(\text{G}) \right]$$
$$subject\ to$$
$$x_t = [x_{t1}, x_{t2}] \quad (7)$$
$$x_r = [x_{r1}, x_{r2}, x_{r3}, x_{r4}]$$
$$0 \leq x_t, x_r \leq 3$$

The multi-objective CMA-ES is applied here to solve the above optimization problem, and find the optimal placement of transmit and receive antennas in a MIMO radar array for a given wall in a theorugh-the-wall imaging scenario.

4 Numerical Results

Assuming we have a single wall radar imaging scene as in Fig.1, with three identical dielectric targets of a radius of 0.2 meter. The dielectric constants and the thickness of the wall are $\epsilon_r = 6$, $\delta = 0.01$ S/m, and $d = 0.3$ meter respectively. An ultra-sparse MIMO array system composed of 2 transmitters and 4 receivers spanning a physical aperture of 3 meters is employed to scan the region of interest. The operating frequency of the system ranges from 1 GHz to 3 Ghz covering 112 evenly spaced frequency bins. The scattered data is simulated using a FDTD based code gprMax [10], and fast Fourier transform (FFT) is performed to obtain the frequency domain data.

Figure 2 shows the direct imaging result using a standard equally spaced MIMO, in which 2 transmitters are positioned at two ends of the antenna array, while the 4 receivers are equally spaced in the middle..Grating lobes and sidelobes are clearly observed to spread surrounding the targets severely.

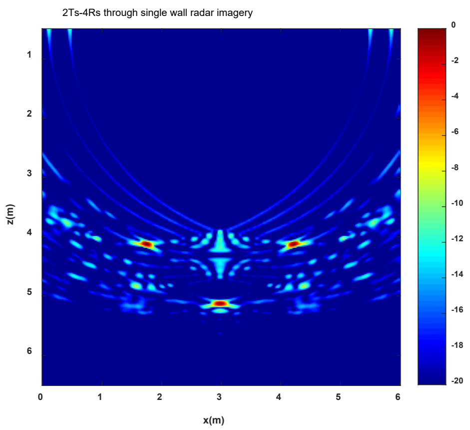

Figure 2: Imaging result using an equally spaced topology

We now conduct a multi-objective optimization approach using CMA-ES to optimize the above proposed two objectives simultaneously for the same target scene. Figure 3 shows the resulted Pareto front. The horizontal axis stands for the averaged grating lobes and sidelobes level, while the vertical axis represents the entropy of the Gram matrix.

Although each solution of Pareto optimal solutions may be regarded as equally good, in practice, we have certain emphases when deploying a radar system. In some cases, we want to have the best sidelobe suppression performance. While in other cases, we want the smallest aperture size with acceptable sidelobe performance. Here, we only examine two extreme optimal solutions on the Pareto front, namely the leftmost solution and the

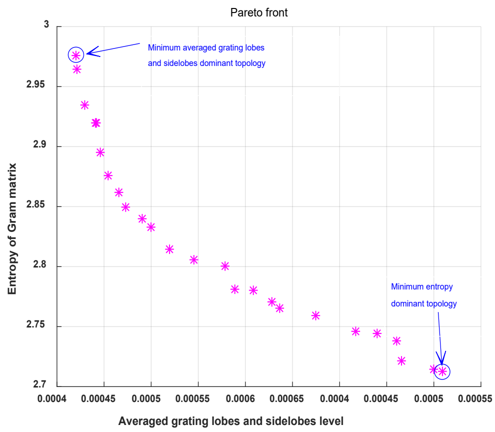

Figure 3: Pareto front for radar imaging through a single-layer wall.

rightmost solution, which correspond to the minimum averaged grating lobes and sidelobes but highest entropy

case, and the severest averaged grating loebs and sidelobes but minimum entropy case, respectively. We call them minimum averaged grating lobes and sidelobes dominant topology and minimum entropy dominant topology, respectively.

Fig.4(a1) and 4(a2) show the minimum averaged grating lobes and sidelobes dominant topology and its imaging result. As can be seen in Fig.4(a2), the sidelobe spreading in non-target region is significantly suppressed when compared to the direct imaging result in Fig.2. For minimum entropy dominant topology as shown in Fig.4(b1), strongly degraded targets profile is obtained in its imaging result in Fig.4(b2). The targets are totally distorted in cross-range dimension. We even can no longer tell the accurate locations of the targets of interest from this result. Although the least grating lobes and sidelobes spreading is achieved in the entire image for this case, its averaged grating lobes and sidelobes level presents to be the highest. The reason lies in the extremely short aperture optimized in this case.

Based on the above simulation analysis, in the context of the array design for radar imaging through a single-layer wall, it is suggested that a wall parameter dependent optimization strategy to be adopted. If we want the smallest averaged grating lobes and sidelobes with acceptable grating loebs and sidelobes spreading, we need then to embrace the minimum averaged sidelobes dominant topology.

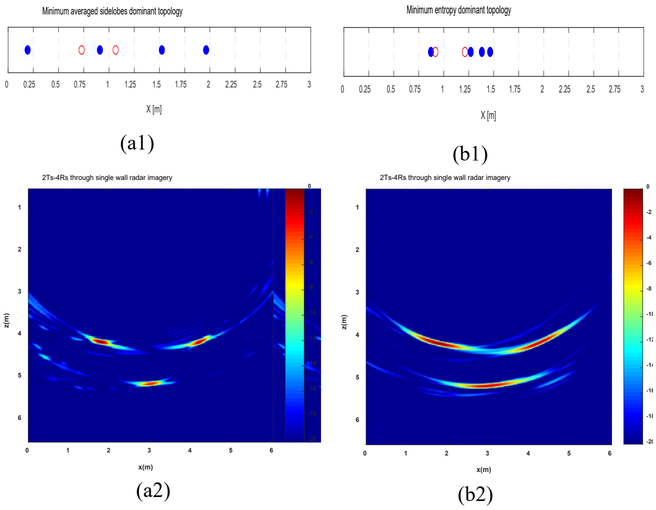

Figure 4: Optimized topologies and corresponding imaging results. (a1), (b1) Minimum averaged grating lobes and sidelobes dominant topology and minimum entropy dominant topology. (a2), (b2) Imaging results corresponding to topologies in (a1) and (b1).

6 Conclusion

In this work we presented a method to consider the wall's effects when designing array topology for TWRI applications. The proposed technique uses a multi-objective CMA-ES based optimization algorithm to minimize an objective function that uses two optimization criteria, one based on minimum averaged grating lobes and the other based on minimum entropy of the synthesizing image operator. Numerical examples showed that a significant improvement of the image quality was achieved using the optimized topology when compared to the imaging results of the wall parameters independent equally spaced array topology. The proposed array design strategy can not only be used for radar imaging in through-the-wall cases but also in GPR applications. Other examples including the case of multilayer wall scenario as well as measured results will be discussed in the presentation.

7 References

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